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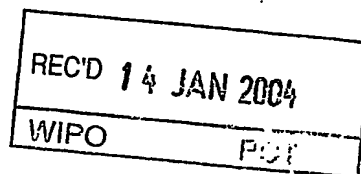## The Kingdom of Norway

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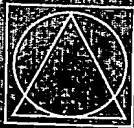
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Oppfinner(e):

Konfigurerbart diffraktiv optisk element

This invention relates to a configurable diffractive optical element comprising an array of diffractive sub-elemenents having a reflective surface.

Configurable Diffractive Optical Elements for Spectral Filtering and Focusing

December 23, 2002

1 Introduction

The decomposition of light into its component frequencies (wavelengths) is fundamental to optical spectroscopy. In this paper we describe a class of optical devices that serve as configurable spectral filters. The devices receive an incident beam composed of light of different frequencies. They direct part of the light in a certain direction or onto a focal point. The devices consist of a system of movable diffractive microstructures on a substrate. By applying different voltages to the device, we alter the relative positions of the microstructures and thus we also alter the spectral composition of the diffracted light.

2 Background

2.1 Spectral filters

Spectral filters are important for all kinds of optical measurements. In the following we use the term *spectral filter* in a broad sense to describe all devices that selectively remove light with specific frequencies, totally or partially, from a lightpath. If the properties of the filter can be changed over time by applying different voltages, temperatures or other means of actuation we call it a tunable or configurable filter. There is no clear distinction between *tunable* and *configurable* except that the latter implies that a larger range of possible filter functions can be realized. Configurable optical filters are particularly important for spectroscopy. One example is the tiltable grating of a conventional monochromator. By our definitions this is an example of a tunable (or configurable) optical filter.

2.2 Configurable Diffractive Optical Elements (CDOEs)

Diffractive optical elements (DOEs) have been around for the past three decades. A diffractive optical element is a generalized 1- or 2-dimensional optical grating or hologram, made to synthesize a light field by exposing different parts of an incident light beam to different phase delays and/or amplitude modulations. With micro-electromechanical systems (MEMS) it is possible to make configurable DOEs. With current silicon micromachining technology it is not difficult to make moving parts with dimensions down to 1 micrometer. In a configurable

DOE (CDOE) the top of such moving parts will be an optical surface: Mirrors, gratings or more complex structures for filtering or focusing. In the following we will call each surface a *diffractive sub-element*. Their relative positions can be tuned with a resolution much less than typical optical wavelengths, and the interference between reflections from the different parts determines the resulting light field.

2.3 Previous Work

A CDOE for synthesizing spectral filters ("The Polychromator") has been designed and implemented by Hocker et al.[1, 2, 3]. This device is an electrostatically controlled array of beams. The beams can move vertically and the top of each beam is reflecting and plays the role as a grating element. The underlying theory of synthetic filters is given by Sinclair[4] and, in more general terms, Fienup[5].

The disadvantage of this solution is that light with a wide spectral range is diffracted at one single angle, limiting the resolution that can be obtained. Higher resolution can be obtained with a larger number of beams, but this increases the complexity of the device and makes it impractical to control. It is also a disadvantage that light cannot be focused onto a detector. This is possible with a concave ruled grating or, as we will show, a focusing diffractive pattern. Finally, the many gaps between the moving grating elements reduce diffraction efficiency.

2.4 Extensions and improvements

There are several possible extensions/improvements of the electrically-programmable diffraction grating. They will be listed below and explained in more detail later.

- A CDOE can be made to focus light. This reduces the need for additional optical components, which may be expensive and require difficult alignment. One way to make a focusing device is to shape the diffractive sub-elements like Fresnel zones or sectors of Fresnel zones.

- A low number of wide sub-elements with a blazed grating surface can be used instead of a high number of narrow sub-elements with a plane reflecting surface. See the difference between Fig. 1 and Fig. 2. For a large group of applications this will both reduce the mechanical complexity of the CDOE and increase diffraction efficiency.

- The phase modulation can also be obtained by moving the beams sideways, i.e. in a direction parallel to the surface. With silicon on insulator (SOI) technology with comb-drives it is possible to make better optical surfaces with fewer process steps.

- The previous examples are all 1-dimensional arrays. Even the Fresnel zone structure can be considered a 1-dimensional array in polar coordinates. In the more general case, the plane of the CDOE can be divided into arbitrary patches, where each patch is a diffractive sub-element with phase modulation by vertical or horizontal movement.

2

3 Theory

The Fraunohofer approximation to far-field diffraction from a plane screen is simply to take the Fourier transform of the optical field at the screen. For one spatial dimension this can be written as

$$U(k\sin\theta) = \mathcal{F}[u(x)] \tag{1}$$

where $k = 2\pi/\lambda$, θ is the diffraction angle and x the screen position. If we were to design a DOE for collimated light with incident angle zero, U would be our target function and $u(x)$ the complex transmission/reflection coefficient of the DOE aperture. U is a function of the product between k and $\sin\theta$—wavelength and angle play the same roles. A DOE can be used to synthesize a spatial(angular) pattern for a fixed wavelength, or a spectral pattern for a fixed angle, or a combination of both. Unless otherwise stated we will in the following consider spectral patterns at a fixed angle and we write $k_x = k\sin\theta$.

To determine the shape of the diffracting surface that produces the target function U in the far-field we make the inverse Fourier transform of Eq. 1:

$$u(x) = \mathcal{F}^{-1}[U(k\sin\theta)] \tag{2}$$

This results in a complex function $u(x)$ where both phase angle and amplitude varies. However it is common that we have some restrictions on $u(x)$, for instance that $|u(x)| = 1$. That means we are limited to, or have chosen to, only control the phase of $u(x)$. In that case we have to resort to a numerical algorithm to find $u(x)$. An example of such an algorithm is the iterative Fourier transform algorithm that has many names and variations. See [5] for an overview.

3.1 An array of beams

Fig. 1.

An array of beams like the "Polychromator" described in section 2.2 is a suitable device to demonstrate basic properties of configurable DOEs and the iterative Fourier transform. Neglecting the space between elements, the complex reflection coefficient of the beam array can be written as

$$u(x) = \exp[i\phi(x)] = \left[\sum_{n=1}^{N} u_n \delta(x - nd)\right] * p(x) \tag{3}$$

$p(x)$ is the reflection coefficient of a single grating element, d is the grating period and $u_n = \exp(i\phi_n)$. For beams with flat reflecting surfaces, $p(x) = \text{rect}(x/d)$.

The Fourier transform of Eq. 3 is

$$U(k_x) = \mathcal{F}\left[\sum_{n=1}^{N} u_n \delta(x - nd)\right] \mathcal{F}[p(x)] = \left[\sum_{n=1}^{N} u_n \exp(-ik_x nd)\right] P(k_x) \tag{4}$$

The sum in the square brackets is just the truncated Fourier series with coefficients u_n. The series is periodic in k_x with period $\Delta k_x = 2\pi/d$. The whole thing is multiplied with the Fourier transform of $p(x)$. In the case that $p(x) = \text{rect}(x/d)$, $P(k_x) = \text{sinc}(k_x d)$ Given a target function U, the coefficients u_n can be determined with an iterative FFT/IFFT algorithm.

As for a regular grating, the highest optical frequency that can be resolved is given by Nd, the product of the number of grating elements and the grating period, while the cutoff frequency or free spectral range is given by the first zero of the sinc envelope function:

$$P(k_x) = \text{sinc}(k_x d) = 0 \iff k_{x0} = 2\pi/d \tag{5}$$

We will explain below how the envelope function can be shifted to higher frequencies.

Many spectroscopy applications require relatively high resolution in a relatively narrow frequency range Δk_x centered on frequency k_c. From Eq. 5 we see that to ensure that k_c is below k_{x0}, the period d has to be sufficiently low—A low d is needed to achieve a wide enough spectral range. But since the resolution goes as Nd, a large N is needed to maintain a high resolution. This results in a complex device where hundreds or thousands of beams have to be individually controlled. Butler et al. [2] have found a way of improving the design of "The Polychromator" where they use an additional grating in the light path. We find it much more convenient to change the surface of the beams themselves. The solution, an array of gratings, is described below.

4 Devices

4.1 An array of gratings

Fig. 2.

The flat tops of the beams in the previous section can be replaced with gratings with grating period $d_S < d$. For a sinusoidal grating we have $p(x) = \text{rect}(x/d)\exp(i2\pi x/d_S)$. We then get $P(k_x) = \text{sinc}(k_x d - 2\pi d/d_S)$. This is essentially a shifting of the sinc envelope of Eq. 5 to the frequency of our choice. The frequency shift is determined by the ratio between the two grating periods. Thus we can achieve spectral filtering with high resolution and a low number of beams/elements.

4.2 Lateral movement

Fig. 3

For collimated light with incident angle α and diffracted angle β the relationship between DOE height h and phase delay ϕ is $\phi = 2\pi h(\cos\alpha + \cos\beta)/\lambda$. It is also possible to achieve a phase delay by moving laterally a beam or part of a CDOE. If an element is moved sideways a distance D, the relation between ϕ and D is $\phi = 2\pi D(\sin\alpha - \sin\beta)/\lambda$, neglecting the contribution from the area surrounding the subelement.

Many MEMS devices are based on SOI structures with lateral movement actuated by electrostatic combdrives. These structures are stiffer and also easier to fabricate than the multilayer polysilicon process often used to make beam structures with vertical movement.

4.3 A focusing device

Fig. 4

Using diffractive subelements with arbitrary shapes, it is possible to make focusing configurable spectral filters. If we shape the subelements as Fresnel Zones corresponding to a given focal length, it can be shown that the intensity in the focus is the same as for a one-dimensional beam array or array of gratings.

It may also be possible to use an array of equally sized rectangular subelements with focusing diffractive patterns. Spectral synthesis with such structures will be different, as the contribution to the diffraction integral from a single element no longer corresponds to a single term in the Fourier series as in Eq. 4.

4.4 A double array

Fig. 5

Making an inverse Fourier transform of the target function as in Eq. 2 gives us a complex function $u(x)$ with phase and amplitude information. We can implement a CDOE with both amplitude and phase control with a double array of gratings, or an array of subelement pairs. If the two subelements have equal vertical position, there is constructive interference with maximum amplitude. If the heights of the subelements differ by value corresponding to π phaseshift, there is destructive interference and we have zero amplitude. The light is diffracted out of the path.

References

[1] G. Hocker *et al.*, "The polychromator: A programmable mems diffraction grating for synthetic spectra," in *Solid-State Sensor and Actuator Workshop*, Hilton Head Island, South Carolina, June 2000, pp. 89–91.

[2] M. A. Butler *et al.*, "A mems-based programmable diffraction grating for optical holography in the spectral domain," in *IEDM*, 2001.

[3] Ricco *et al.*, "Electrically-programmable diffraction grating," US Patent 5,757,536, 1995.

[4] M. B. Sinclair *et al.*, "Synthetic spectra: a tool for correlation spectroscopy," *Applied Optics*, vol. 36, no. 15, 1997.

[5] J. Fienup, "Phase retrieval algorithms: a comparison," *Applied Optics*, vol. 21, no. 15, pp. 58–69, 1982.

5   Figures

The prior art:

US 5,905,571 Optical apparatus for forming correlation spectrometers and optical processors. This patent describes an optical apparatus for forming correlation

5 spectrometers and optical processors. The optical apparatus comprises one or more diffractive optical elements formed on a substrate for receiving light from a source and processing the incident light. The optical apparatus includes an addressing element for alternately addressing each diffractive optical element thereof to produce for one unit of time a first correlation with the incident light, and to produce for a different unit of time

10 a second correlation with the incident light that is different from the first correlation. In preferred embodiments of the invention, the optical apparatus is in the form of a correlation spectrometer; and in other embodiments, the apparatus is in the form of an optical processor. In some embodiments, the optical apparatus comprises a plurality of diffractive optical elements on a common substrate for forming first and second gratings

15 that alternately intercept the incident light for different units of time. In other embodiments, the optical apparatus includes an electrically-programmable diffraction grating that may be alternately switched between a plurality of grating states thereof for processing the incident light. The optical apparatus may be formed, at least in part, by a micromachining process.

20

US 5,757,536 Electrically-programmable diffraction grating. This patent describes an electrically-programmable diffraction grating. The programmable grating includes a substrate having a plurality of electrodes formed thereon and a moveable grating element above each of the electrodes. The grating elements are electrostatically

25 programmable to form a diffraction grating for diffracting an incident beam of light as it is reflected from the upper surfaces of the grating elements. The programmable diffraction grating, formed by a micromachining process, has applications for optical information processing (e.g. optical correlators and computers), for multiplexing and demultiplexing a plurality of light beams of different wavelengths (e.g. for optical fiber

30 communications), and for forming spectrometers (e.g. correlation and scanning spectrometers).

This solution also has the disadvantage of having to control a large number og elements.

Also it is difficult to obtain large enough resolution within a small spectral range
because of the demand for a large grating and the practical limits to the minimum size
of the elements and the distance between them. Also nature of the need for individual

5   control of each grating element provides a complicated solution.

It is the object of this invention to provide a configurable diffractive
optical element providing a good resolution within a chosen frequency range,
e.g. for spectral interrogations, with a low number of electrically actuated

10   parts. The invention also provides focusing of the light beam, eliminating
the need for additional optical components.

This is obtained using an element according to the accompanying claims.

The invention will be described below with reference to the accompanying drawings,

15   illustrating the invention by way of examples.

Figure 1   illustrates the known art in which the grating is constituted by the relative
                position between a number of reflectove, plane surfaces.

Figure 2   illustrates the principle of the present invention.

Figure 3   illustrates a first alternative embodiment of the invention.

20   Figure 4   illustrates a second alternative embodiment of the invention

Figure 5   illustrates a third embodiment of the invention in which the sub-elements
                constitutes a two-dimensional array.

The known art as illustrated in figure 1 comprises an array of reflective elements 1
which may be moved relative to each other so as to provide a grating, as discussed

25   under sections 2.3 and 3.1 above. Because of the construction of this device there are
strict limits to the mature of the grating. For example it is difficult to make grating
periodes less than 10 μm resolution since the each grating sub-element must be
individually controllable. Thus the resolution of these gratings are not sufficient for
purposes such as spectroscopy.

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As is described above in sections 4.1, 4.2, 4.3 and 4.4 above the and illustrated in
figures 2-5 the present invention provides a solution with larger subelements 2 in which

each subelement is provided with a grating. The grating on each subelement may be provided with any suitable grating periode without other limitations than the ones present in the production of ordinary gratings.

5   The dimensions of the diffractive subelements according to the invention should correspond to a number of periodes for the gratings on each subelements, e.g. in the range of 150 μm.

Thus it is possible to provide an adjustable diffractive grating with a higher resolution
10   than the similar gratings according to the known art, thus being more suitable e.g. for spectroscopic studies, spectral filtering etc.

The beams or subelements according to figures 2, 4 and 5 may be moved in a directions perpendicular to the element surface. In figure 3, however, as described above, the
15   positions of the subelements may be shifted in the lateral direction parallel to the surface. Any combinations of these movements are of course possible, although more complicated to obtain in practice. Typically the movement relative to direction of the incoming or reflected light should be in the order of ½ the wavelength of the light.

C l a i m s

1.   Configurable diffractive optical element comprising an array of diffractive sub-elemenents having a reflective surface, wherein each sub-element has a controllable position with a chosen range, and in which a number of sub-elements are provided with
5   a reflective grating with a number of chosen spectral characteristics.

2.   Diffractive optical element according to claim 1 wherein the physical size of each diffractive sub-element is substantially larger than the typical spatial period of the diffractive pattern on each sub-element
10

3.   Diffractive optical element according to claim 1 wherein the position of each sub-element is adjustable in a direction perpendicular to the element surface.

4.   Diffractive optical element according to claim 1 wherein the position of
15   each grating element is adjustable in a direction parallel to the element surface.

5.   Diffractive optical element according to claim 1 wherein the position of each grating element is adjustable in a direction parallell to the optical axis of the incoming or reflected light beam.
20

6.   Diffractive optical element according to claim 1 wherein the gratings on the grating element surfaces constitutes a diffractive lens.

25   7.   Diffractive optical elementaccording to claim 1 wherein the array of diffractive sub-elemenents is a twodimensional array.

Abstract

This invention relates to a configurable diffractive optical element comprising an array of diffractive sub-elemenents having a reflective surface, wherein each sub-element has a controllable position with a chosen range, and in which a number of sub-elements are provided with a reflective grating with a number of chosen spectral characteristics.

<u>Figure 2</u>
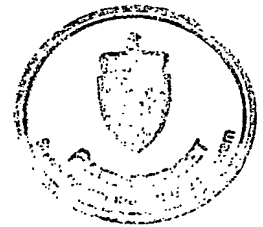
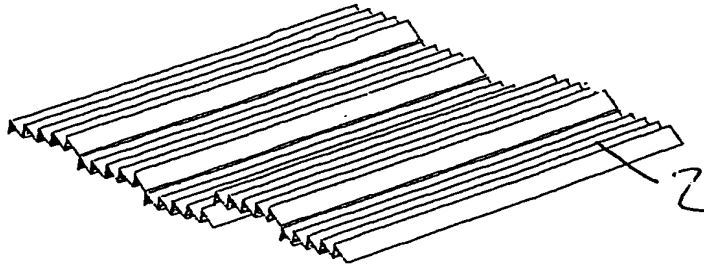beamArray
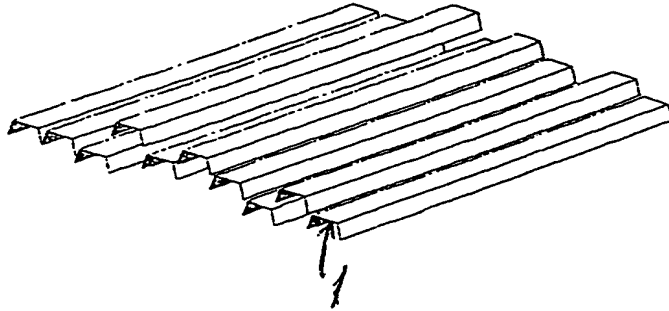
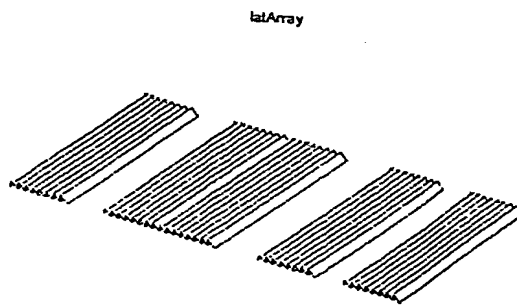Figure 1: beam array

gratingArray

Figure 2: grating array

latArray

Figure 3: lateral movement array

focusArray
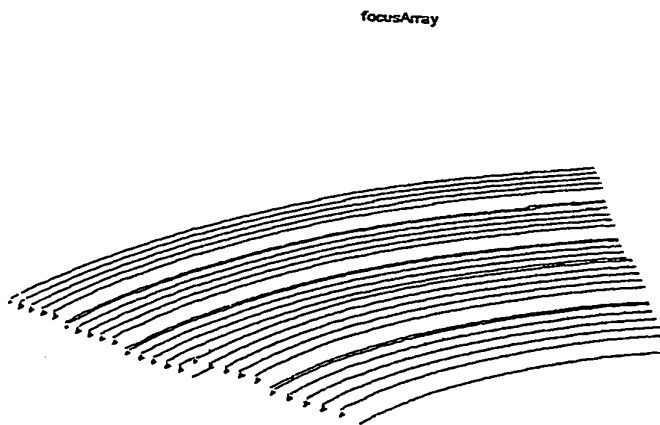
Figure 4: focusing array
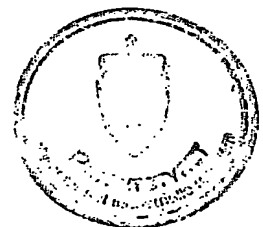
doubleArray

Figure 5: double array